INL/CON-11-24139
PREPRINT

Assessment of Possible Cycle Lengths for Fully-Ceramic Micro-Encapsulated Fuel-Based Light Water Reactor Concepts

PHYSOR 2012

R. Sonat Sen
Michael A. Pope
Abderrafi M. Ougouag
Kemal Pasamehmetoglu

April 2012

ASSESSMENT OF POSSIBLE CYCLE LENGTHS FOR FULLY-CERAMIC MICRO-ENCAPSULATED FUEL-BASED LIGHT WATER REACTOR CONCEPTS

R. Sonat Sen, Michael A. Pope, Abderrafi M. Ougouag, Kemal Pasamehmetoglu
Idaho National Laboratory
P.O. Box 1625, Idaho Falls, ID 83415-3840, USA
sonat.sen@inl.gov, michael.pope@inl.gov, abderrafi.ougouag@inl.gov,
kemal.pasamehmetoglu@inl.gov

Francesco Venneri
UltraSafe Nuclear
fvenneri@ultrasafe-nuclear.com

ABSTRACT

The use of TRISO-particle-based dispersion fuel within SiC matrix and cladding materials has the potential to allow the design of extremely safe LWRs with accident-tolerant fuel. This paper examines the feasibility of LWR-like cycle length for such a low enriched uranium fuel with the imposed constraint of strictly retaining the original geometry of the fuel pins and assemblies. The motivation for retaining the original geometry is to provide the ability to incorporate the fuel "as-is" into existing LWRs while retaining their thermal-hydraulic characteristics.
The feasibility of using this fuel is assessed by looking at cycle lengths and fuel failure rates. Other considerations (e.g., safety parameters, etc.) were not considered at this stage of the study. The study includes the examination of different TRISO kernel diameters without changing the coating layer thicknesses.
The study shows that a naïve use of UO_2 results in cycle lengths too short to be practical for existing LWR designs and operational demands. Increasing fissile inventory within the fuel compacts shows that acceptable cycle lengths can be achieved. In this study, starting with the recognized highest packing fraction practically achievable (44%), higher enrichment, larger fuel kernel sizes, and the use of higher density fuels have been evaluated. The models demonstrate cycle lengths comparable to those of ordinary LWRs.
As expected, TRISO particles with extremely large kernels are shown to fail under all considered scenarios. In contrast, the designs that do not depart too drastically from those of the nominal NGNP HTR fuel TRISO particles are shown to perform satisfactorily and display a high rate of survival under all considered scenarios.
Finally, it is recognized that relaxing the geometry constraint will result in satisfactory cycle lengths even using UO_2-loaded TRISO particles-based fuel with enrichment at or below 20 $^{w}/_{o}$.

Key Words: Fully-Encapsulated, FCM, Microstructure, TRISO, PWR

1. INTRODUCTION

The tri-isotropic (TRISO) fuel developed for High Temperature Reactors (HTRs) is known for its extraordinary fission product retention capabilities [1]. Recently, the possibility of extending the use of TRISO particle fuel to Light Water Reactor (LWR) technology, and perhaps other reactor concepts, has received significant attention [2]. In the framework of the Deep Burn (DB) project, once-through burning of transuranic fissile and fissionable isotopes (TRU) in LWRs was investigated [3]. The fuel form for this purpose, known as Fully-Ceramic Micro-encapsulated (FCM) fuel, embodies a concept that borrows the TRISO fuel particle design from high temperature reactor technology, but uses silicon carbide (SiC) as a matrix material rather than graphite. In addition, FCM fuel may also use a cladding made of a variety of possible materials, again including SiC as an admissible choice. Such a concept in the context of LWRs was proposed by Venneri [4], Snead [5] and their co-workers.

In multiple previous computational model-based studies, the FCM fuel used in the Deep Burn (DB) project showed promising results in terms of fission product retention at high burnup values and during high-temperature transients. In the case of DB applications, the fuel loading within a TRISO particle was constituted entirely of TRU from spent LWR fuel. Consequently, the fuel was shown to be capable of achieving reasonable burnup levels and cycle lengths, especially in the case of mixed cores (with coexisting DB and conventional LWR UO_2 fuels). The purpose of this paper is the examination of the direct and simple replacement of LWR fuel pellets by compacts of FCM fuel with a strict retention of the initial geometry for the pellets and surrounding cladding. The intent is to assess the feasibility of assembly designs that match exactly the configuration of existing LWR fuels and that retain their thermal-hydraulics characteristics. It is recognized that such a constraint is very severe and that it may lead to highly undesirable short cycle lengths if enrichment is deliberately kept below 20 $^w/_o$, beyond which the fuel is no longer considered low-enrichment. The relaxation of either of these constraints can be shown to result in acceptable cycle lengths. In particular, allowance for geometry variations (while retaining the low enrichment levels) was considered in other work to be presented later.

Within the constraints discussed above, the initial focus of this paper is on the use of TRISO particles with up to 20 $^w/_o$ enriched uranium dioxide kernels loaded in Pressurized Water Reactor (PWR) assemblies corresponding to *existing* LWR designs. In addition to consideration of this "naïve" use of TRISO fuel in LWRs, several refined options are briefly explored and others are identified for further consideration, including the use of advanced, high density, fuel forms and larger kernel diameters and TRISO packing fractions. The combination of 800 μm diameter kernels of 20 $^w/_o$ enriched uranium nitride (UN) and a near 50% TRISO packing fraction (PF) yields a reactivity level sufficiently high to achieve burnup objectives comparable to those expected from present generation PWR fuel. This is in contrast to the "naïve" approach that shows the use of UO_2-only FCM fuel in a LWR results in considerably shorter cycle length when compared to current-generation ordinary LWR designs. Indeed, the constraint of limited space availability for heavy metal loading within the TRISO particles of FCM fuel and the constraint of low (i.e., below 20 $^w/_o$) ^{235}U enrichment combine in this latter case to result in shorter cycle lengths compared to ordinary LWRs if typical LWR power densities are also assumed and if typical TRISO particle dimensions and UO_2 kernels are specified.

As stated above, the relaxation of the geometric constraints on the fuel pellets, fuel pins, and fuel assembly designs can result in acceptable fuel cycle lengths. Evidence that this is the case can be found in several unrelated studies [6,7,8,9]. These studies represent an extreme in geometry changes that could result in extremely long cycle (even up to 30 years [9]), while this paper presents the other extreme of retaining the original geometry. It is obvious that intermediate changes in geometry may be considered that would result in intermediate cycle lengths, including cycle lengths that match those of existing LWRs.

Another way of improving cycle length performance would be to include a higher density of fissile nuclides. If enrichment must remain limited, this can be achieved through the use of higher packing fractions of TRISO particles in the matrix and of higher density fuels. The packing fraction is limited by fuel integrity considerations to no more than 44% [10]. The use of higher fuel, in which the density of uranium is greater than in UO_2 has been considered by others in the context of dispersion fuels, albeit not TRISO-based ones [11, 12]. In this work both this higher density fuel (uranium silicide, U_3Si) and uranium nitride (UN) are examined in the context of their use within dispersed TRISO particles.

2. METHODOLOGY

This study relies on extensive reactor physics-based performance modeling. The necessary computations are performed using DRAGON-4, an open source lattice physics transport code developed and maintained by École Polytechnique de Montréal [13]. The code incorporates multiple solution methods and allows flexible calculation routes and data manipulation. In particular, it includes a capability for the direct treatment of the double heterogeneity arising from the fuel morphology as dispersed TRISO particles within a fuel matrix. This capability uses the method developed by Hébert [14]. Collision probability calculations were performed using a cross section library generated from ENDF/B-VII.0 and cast in the SHEM-281 energy group structure [15].

Unit cell depletion calculations were performed to evaluate the FCM fuel. Each type of fuel investigated was depleted based on a flux calculation using a B_0 buckling search. Single cell calculations can be informative with regard to the performance of the fuel under consideration, especially when a whole core is loaded with similar fuel. The information is also useful when the core is "zoned" and the fuel under consideration is loaded in only parts of the core. It is then possible to determine when the zone is a driver (i.e., has an infinite multiplication factor, k_∞, greater than 1.0) and when it becomes driven (i.e., at what point the zone has a k_∞ lower than 1.0). The presence of driven zones shortens the cycle i.e, the time between required refueling outages, though they contribute to achieving higher burnup levels.
Table I shows the dimensions and densities of the layers of the typical TRISO particles selected for the initial calculations. These specific TRISO particles correspond to the design specified in the HTRs considered by the NGNP project and are the TRISO designs that have been most extensively tested experimentally and that were shown to sustain extended burnup without failure. In the present study, as a simplifying assumption, the kernel diameter was varied without changing the coating layer thicknesses, the implications of this assumption on the fuel performance are shown later in the text.

Table I. TRISO fuel particle dimensions and physical properties for initial studies.

Layer	Thickness (μm)	Density (g/cm^3)
Kernel (UO_2)	500*	10.4
Porous Carbon Buffer	100	1.05
Inner Pyrolytic Carbon	35	1.9
Silicon Carbide	35	3.18
Outer Pyrolytic Carbon	40	1.9

* This is the kernel diameter, which is varied in the analysis.

Table II gives parameters for the reactor design assumed to apply in *this* stage of the study. The basic parameters are taken from a typical modern PWR, specifically the AREVA EPR™ design [16]. The assumed power rating is 4500 MW_{th} and the number of 17x17 fuel assemblies is 241. The oxide fuel ordinarily used as pellets in the EPR design is simply replaced with fuel compacts having a TRISO particle PF of 44%, which has been estimated to be the maximum packing feasible without causing excessive failures [10]. The Zircaloy fuel cladding material is also replaced by silicon carbide (SiC).

As a simplifying assumption and to compare on a consistent basis, all fuel types studied in this work were assigned the same temperature of 900ºC to represent nominal conditions

Table II. Characteristics of PWR Assembly and Core Analyzed.

Parameter	Value
Reactor Thermal Power (MW_{th})	4500
Number of Fuel Assemblies	241
Active Fuel Height (cm)	420
Assembly Pitch (cm)	21.504
Actual Pin Pitch (cm)	1.270
Effective Pin Pitch for Single Cell Calculations (cm)	1.320
Number of Fueled Pins per 17x17 Assembly	265
Number of Guide Tubes per 17x17 Assembly	24
Fuel Pellet Diameter (cm)	0.820
Fuel Pin Inner Diameter (cm)	0.836
Fuel Pin Outer Diameter (cm)	0.950
Guide Tube Inner Diameter (cm)	1.140
Guide Tube Outer Diameter (cm)	1.230
Average Linear Power (kW/m)	16.7
Average Power per Volume of Core (MW_{th}/m^3)	96.2
Average Power per Volume of Fuel Pellet (MW_{th}/m^3)	318

3. RESULTS

This section reports the results of the study beginning with those from ordinary PWR fuel and fuel containing typical TRISO particles (fueled with UO_2). Later parts of this section examine the use of TRISO particles that incorporate fuel compositions with higher heavy metal specific loading (i.e., U-atoms per unit volume).

3.1. Neutronic performance of conventional TRISO particles

The fissile (U-235) inventory of a FCM fuel compact loaded with TRISO particles (PF=44%) containing 20 $^{w}/_{o}$ enriched uranium is 31% of the fissile inventory of an ordinary LWR pellet of the same size. It is therefore expected that the fissile inventory would be reduced to levels incapable of sustaining a continuing chain reaction after operating the FCM-based reactor for a much shorter time than the ordinary-fueled reactor. Figure 1 shows k_∞ versus burnup expressed in Effective Full Power Days (EFPD) for the unit cell containing 4.5 $^{w}/_{o}$ enriched UO_2 fuel pellets along with TRISO particle fuel containing both 19.9 $^{w}/_{o}$ and 4.5 $^{w}/_{o}$ enriched UO_2 kernels. This shows that the limited amount of heavy metal loading in TRISO fuel yields a much shorter cycle length than that of typical PWR fuel, even with 19.9 $^{w}/_{o}$ enriched UO_2 in the kernels. For the remainder of the analyses presented in this paper, the enrichment is fixed at 19.9 $^{w}/_{o}$.

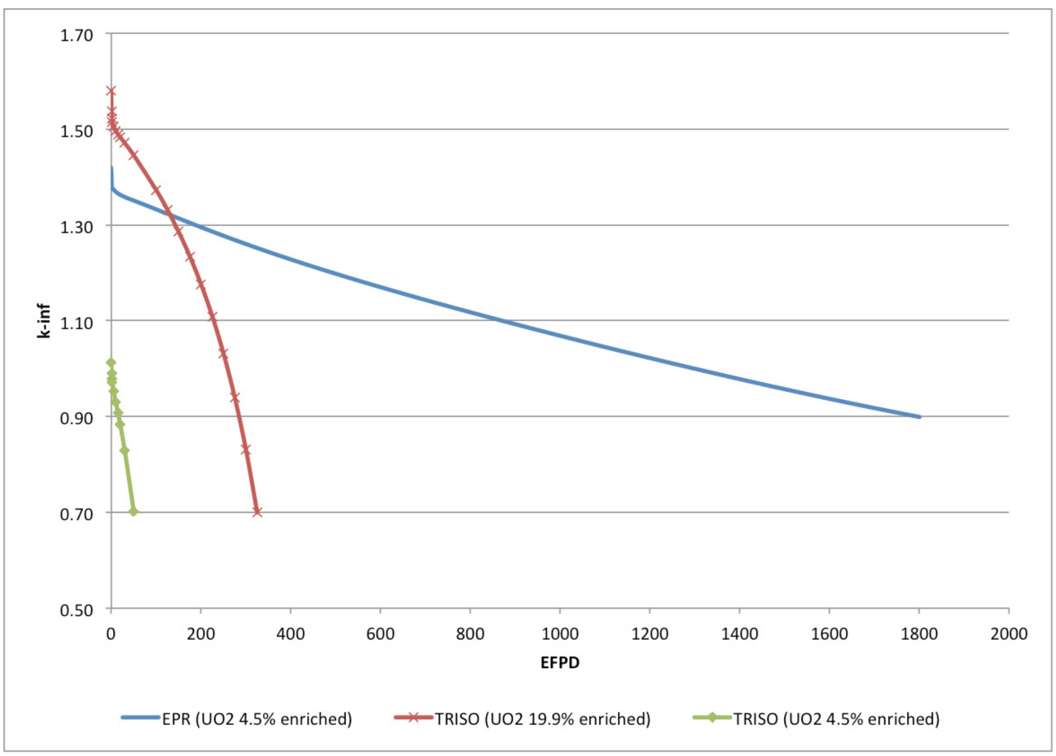

Figure 1. k_∞ versus burnup in EFPD for conventional PWR fuel and TRISO particles in SiC matrix.

The effective heavy metal (HM) density for a fuel pellet containing typical TRISO particles (i.e., TRISO particles with 500 μm diameter kernels) and with a 44% TRISO particle packing fraction is 0.65 gHM/cm^3, whereas it is 9.2 gHM/cm^3 for ordinary UO_2 fuel. If the FCM-loaded assembly is to be used such as to yield the same power density as an ordinary LWR assembly, there results a corresponding requirement that the fuel-specific power be quite demanding. Namely, the difference in fuel loading imposes a specific power requirement of 491 MW/MTU for the FCM fuel kernels, while the ordinary LWR fuel is normally used at a power density of about 34.7 MW/MTU. This difference is a consequence of the comparatively much smaller amount of space available for actual fuel kernels in this particular embodiment of TRISO fuel (approximately 7% of the volume of the fuel compact sized the same as a LWR pellet) than the space available for fuel in the actual LWR pellet (i.e., the entire 100% of the pellet volume). This difference in fuel loading is only *partly* offset by enrichment to 20 $^{w}/_{o}$ in the FCM kernels versus about 5 $^{w}/_{o}$ in the LWR pellets.

The achievement of an acceptably-long cycle with FCM fuel while maintaining uranium enrichment below 20 $^{w}/_{o}$ requires that the heavy metal loading per fuel compact be increased from the level achievable with the ordinary TRISO geometric design discussed above. In order to increase the heavy metal loading in fuel compacts based on TRISO particles, the kernel diameter or the packing fraction can be increased. In the above considerations, the latter is believed to be near the feasible limit beyond which excessive failures could result [10]. The former is investigated here and discussed below.

Figure 2 shows the neutron infinite multiplication factor, k_∞, versus burnup (quantified in terms of Effective Full-Power Days -- EFPD) for fuel containing TRISO particles with enlarged kernel diameters. A major simplifying assumption made at this stage is that TRISO coating layers are left at their initial respective thicknesses regardless of kernel size. The figure shows that the kernel diameter needs to be increased from 500 μm to 2000 μm in order for a fuel compact to incorporate an amount of fissile material comparable (~10% higher) to that contained in a PWR fuel pellet of outer dimensions identical to those of the FCM fuel compact. With this change in kernel diameter, the cycle length is increased and the k_∞ falls below 1.0 only after about 1100 EFPD, which may lead to an acceptable cycle length in a 3-batch scenario. The beginning-of-life (BOL) reactivity for the FCM fresh fuel is much larger than that of ordinary PWR fuel. The excess reactivity at BOL could be reduced through the incorporation of burnable poison if deemed necessary.

The discussion presented above concerned only the neutronic feasibility of the fuel. It did not address the material feasibility. Conclusions regarding the material performance of these extreme TRISO designs are presented later in this paper.

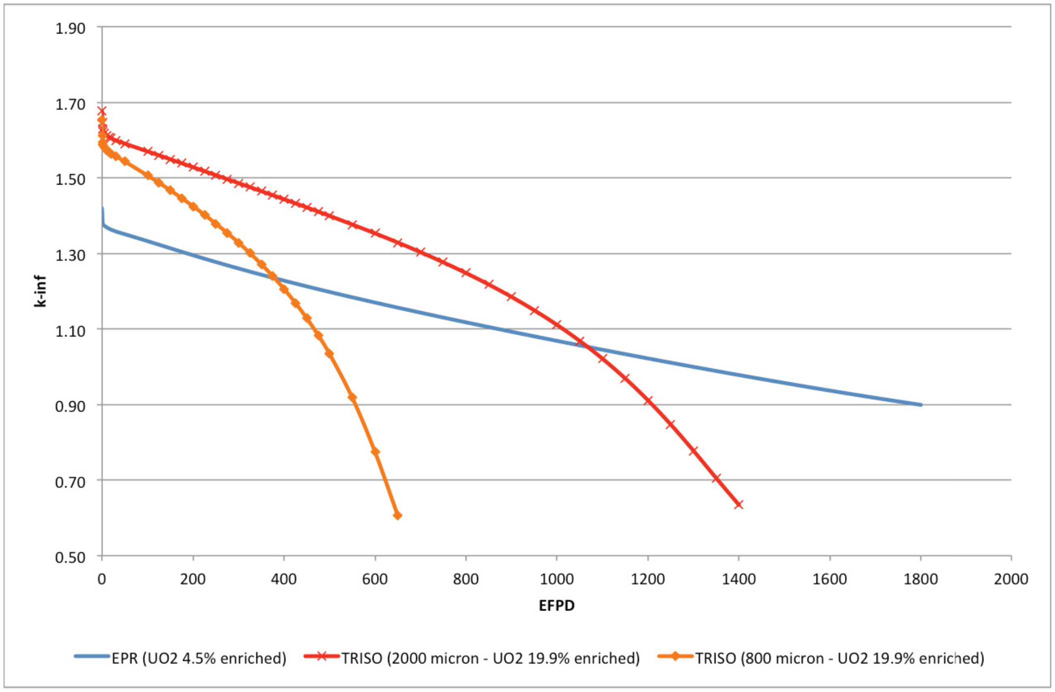

Figure 2. k_∞ versus burnup in EFPD for fuel containing TRISO particles with enlarged kernel diameter.

3.2. Neutronic performance of higher-metal-density fuels

Another path to increasing the heavy metal loading of the FCM fuel is to use a fuel form that possesses a higher heavy metal density than UO_2. Many different dispersion fuel types were previously investigated for used in research and test reactors [11,12]. One such fuel type uses uranium silicide (U_3Si) as the dispersed phase. U_3Si was chosen as the initial material to be investigated here as a means for increasing the cycle length. This choice was motivated by the high density of this material (15.1 g/cm^3 total, 14.5 g/cm^3 heavy metal).

Figure 3 shows k_∞ versus burnup in EFPD for TRISO particles containing U_3Si fuel kernels of varying sizes, all with PF=44%. The largest TRISO heavy metal loading yields a higher cycle length when compared to UO_2 fuel in TRISO particles (Figure 1) however the cycle for the smallest of the kernel diameters is still significantly shorter when compared to that possible with ordinary PWR fuel.

However as mentioned earlier, the feasibility of manufacturing this type of fuel and the effects of the larger kernel diameters on the fuel performance would need further investigation. Overall, it is noteworthy that higher fuel loading in TRISO particles results in reasonable cycle lengths. Even if this level of fuel loading cannot be achieved in practice by using larger kernels within TRISO particles, this study shows that if the loading is achieved through other means, the desirable cycle lengths could be achievable.

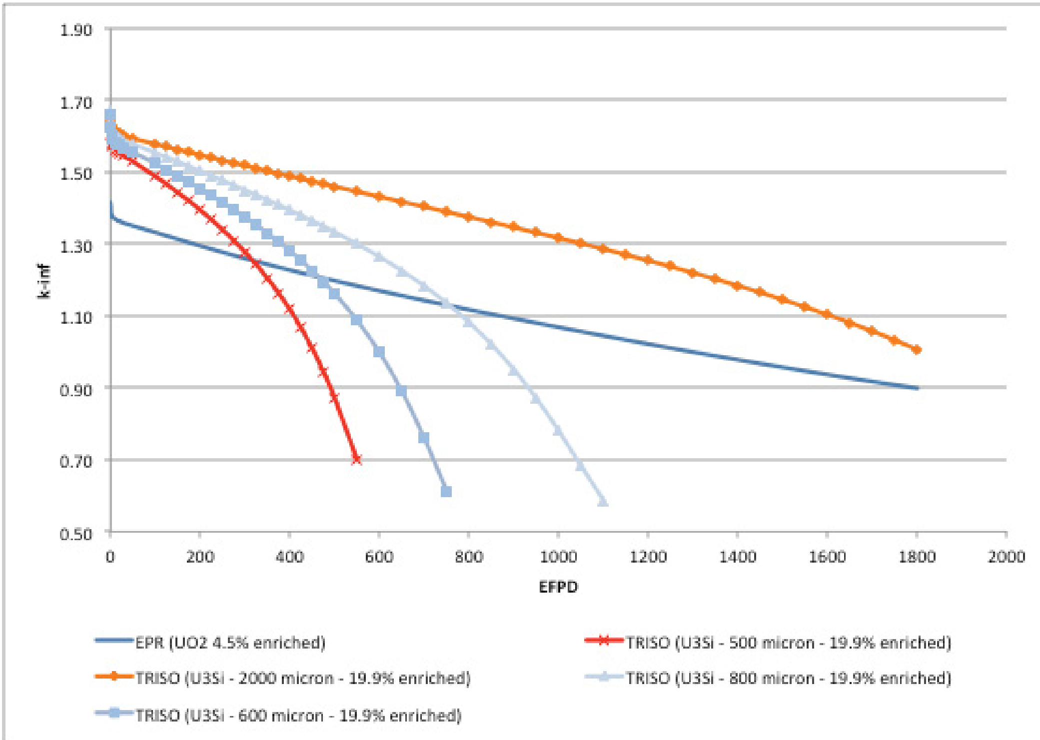

Figure 3. k_∞ versus burnup in EFPD for U_3Si fuel containing TRISO particles.

Some of the selected cases shown previously were also analyzed using the Scale/Triton code [17] in order to confirm the Dragon analysis results. For these selected case, Figure 4 shows comparisons of the results obtained using the Dragon and Scale/Triton codes. The Figure shows that the two codes agree very well in their prediction of k_∞ versus burnup.

Besides U_3Si, other materials could be viable fuels. In Table III some important physical properties are shown for UO_2, U_3Si, and UN fuel. The U_3Si fuel has the highest uranium density when compared to other two fuel materials; however it has a low melting point, which makes it less desirable. This fuel type was thus discarded from further analysis and uranium nitride (UN) was adopted instead. Like U_3Si fuel, the UN fuel possesses the advantage of a much larger thermal conductivity than that of UO_2. Though it does not have as high a heavy metal density as U_3Si, the heavy metal density of UN is approximately 50% higher than that of the UO_2, furthermore, the UN fuel has a very high melting point.

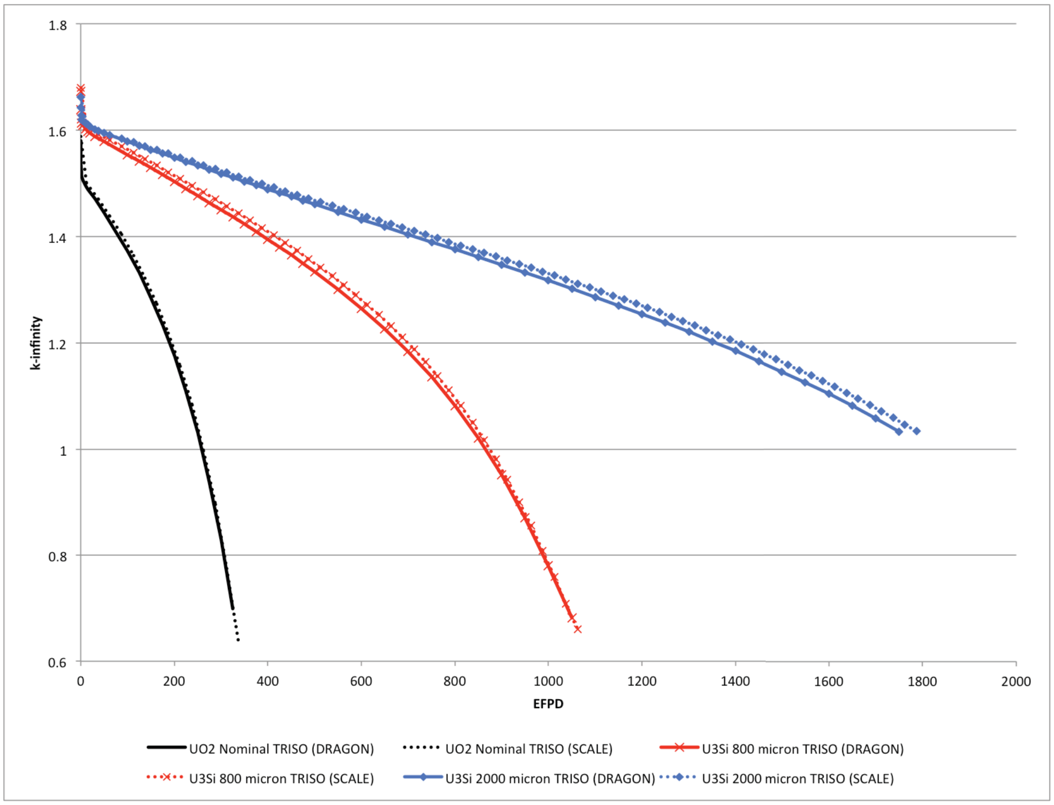

Figure 4. Comparison between Scale/Triton and Dragon codes: k_∞ versus burnup for various fuel types.

Table III. Physical properties of selected fuel materials.

Fuel material	Uranium density (g/cm^3)	Melting Point (^{o}C)	Thermal Conductivity (W/m·K)
UO_2	9.7	2865	3.6 (200 ⁻ 1000 ^{o}C) [18]
U_3Si	14.6	950	24.2 – 38.1 (200 ⁻ 500 ^{o}C) [19]
UN	13.5	2600	21 (200 ⁻ 1000 ^{o}C) [18]

Figure 5 shows k_∞ versus burnup in EFPD for UN fuel in TRISO particles of 800 μm diameter kernels compared to U_3Si fuel TRISO particles of the same size, again all with PF=44%. The reactivity of the UN fuel decreases more quickly than that of the U_3Si fuel due to the lower heavy metal density. However, for the 800 μm diameter case, the cycle length is beginning to approach the cycle length of typical PWR fuel.

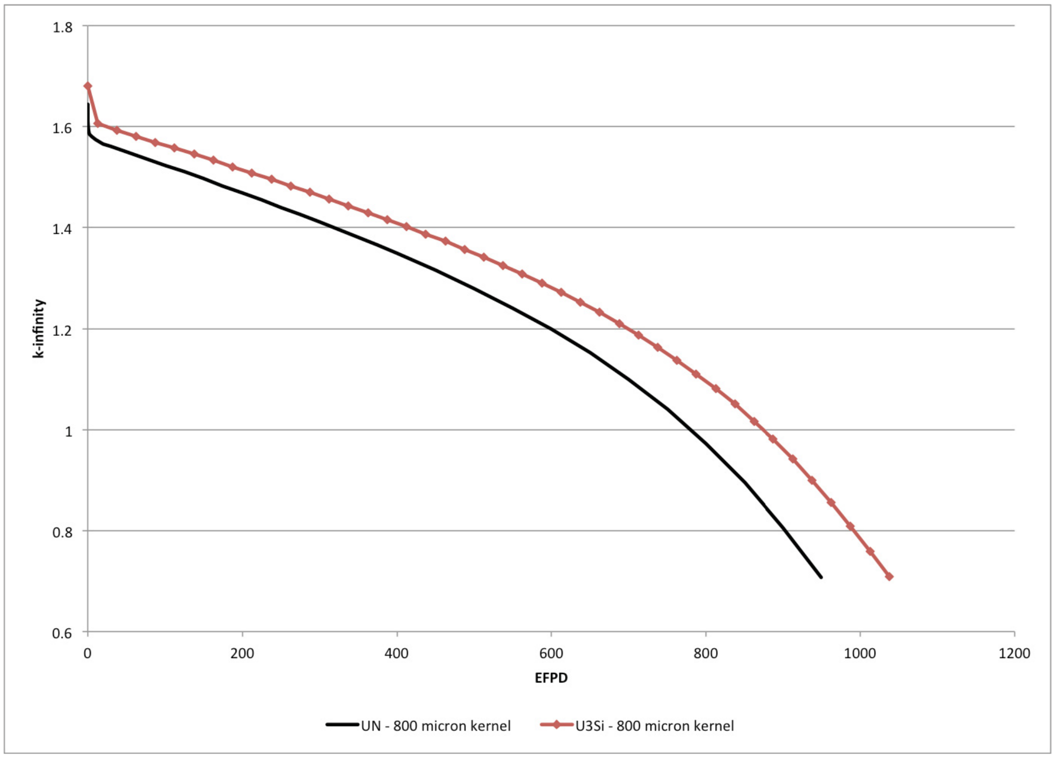

Figure 5. k_∞ versus burnup in EFPD for UN and U_3Si TRISO fuel with 800 μm kernels.

The value of k_∞ remains larger than 1.2 for a full 600 days, which suggests that the fuel could be used in driver assemblies when starting from its fresh state while bundles that have already experienced burnup beyond this time or even beyond the time at which the k_∞ drops below 1.0 could be used as driven assemblies in a two- or three-batch schemes. In such schemes, the cycle lengths would be comparable to those of ordinary LWRs.

3.3. Material performance of FCM fuels under LWR conditions

The neutronic performance and feasibility of reasonably long cycles were presented above. However, whereas it is known from the NGNP project that TRISO particles with a 500 μm diameter kernel exhibit very high material integrity, insufficient information is available for the other kernel sizes. The Advanced Gas Reactor (AGR) experiments, which are being conducted using the Advanced Test Reactor at the Idaho National Laboratory involve TRISO particles containing UCO and UO_2 fuel having kernel diameters between 350 and 510 μm. The results from AGR-1 (UCO only) have demonstrated excellent fuel integrity and no fuel failures occurred during the irradiation to peak burnups in excess of 19% fraction of initial metal atoms (FIMA) [20].

In this section, some conclusions are presented that are based on model results obtained using the PASTA code [21]. It is important to note that the results are mere guidelines and that experimental confirmation must be sought, and no definitive conclusion may be drawn on manufacturability, durability, or continued physical integrity under irradiation and other reactor conditions, until an experimental confirmation has been carried out.

In particular, the ultimate acceptability of TRISO fuel with whatever kernel size remains predicated on the pre-requisite demonstration of its continued physical integrity under irradiation to target burnup levels and under normal as well as off-normal situations.

In this work, fuel performance analyses were performed for the selected fuel materials and TRISO designs using the TRISO fuel performance code PASTA. For these analyses, the fuel thermal conductivities were neglected and the temperature was held constant at 900 K to be consistent with the neutronic analysis as described in the previous sections. This is tantamount to assuming that the kernel and all layers of the TRISO particle are held at the same temperature. Also note that free oxygen production was assumed not to occur and no oxygen getter is used in any of the cases for the neutronic, nor the fuel performance analysis. This assumption neglects the effect of oxygen pressure and is equivalent to assuming the presence of chemically-perfect getter that is neutronically fully transparent and yet does not displace any fuel. Table IV shows the maximum SiC layer stress and the predicted failure fractions for different TRISO particle dimensions and fuel materials. Note that all results shown in Table IV are for PF=44%. It is also noteworthy that the TRISO particles with 2000 μm kernels are all predicted to fail, which should be expected since the SiC layer used in the study is one that is designed to a 500 μm kernel and the pressures that would build from a 2000 μm kernel would overwhelm the thin SiC layer.

The buffer layer thickness was varied for the UN fuel based on 800 μm TRISO kernels and PF=44%. The reactivity effects of the change in the buffer layer thickness are given in Figure 6. Although the smaller thickness of the buffer layer (50 μm) increases the cycle length for a given TRISO packing fraction, the particle failure rate increases significantly. The larger buffer layer thickness (125 μm) decreases the cycle length while reducing the failure fraction significantly. The effect of the fast fluences on the fuel performance is significant and the failure fraction increases with increasing fluence. The fast fluence values for the fuel designs with thinner buffer layer are higher than the one with125 μm thick buffer layer due to the longer cycle length, which yields a higher failure fraction. Nonetheless, failure rates on the order of 10^{-4} may be acceptable for SiC-clad PWR fuel. A more detailed analysis aimed at reducing the fast fluence is left for further studies.

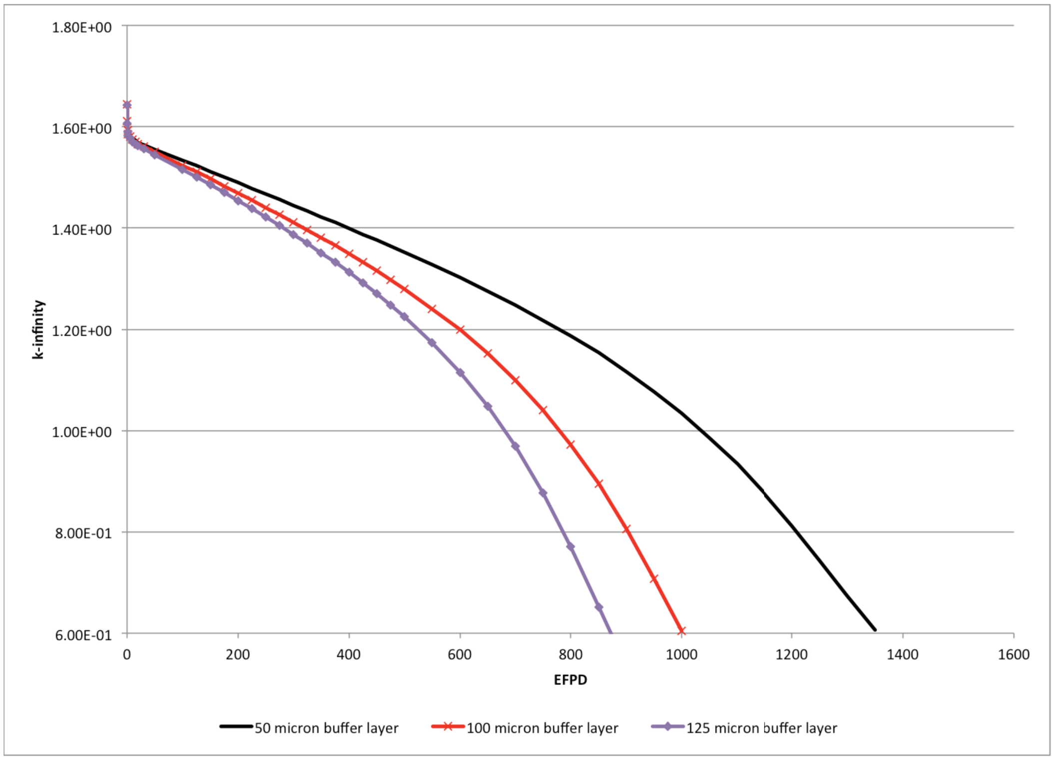

Figure 6. Effect of buffer layer thickness on k_∞ versus burnup.

Table IV. Fuel performance results for various TRISO particles at 44% packing fraction.

Fuel	Kernel diameter (μm)	Buffer Layer thickness (μm)	SiC Stress (MPa)	Failure Fraction
UO_2	500	100	0.00	0.00E+00
	800	100	0.00	0.00E+00
	2000	100	8306	1.00E+00
U_3Si	500	100	0.00	0.00E+00
	800	100	15	1.52E-02
	2000	100	1776	1.00E+00
UN	500	100	0.00	0.00E+00
	800	50	463.85	0.96E+00
	800	100	67.51	2.14E-04
	800	125	0.00	0.00E+00
	2000	100	2072	1.00E+00

Finally, as shown in Figure 7, preliminary work exploring the use of larger fuel pins has indicated that it is possible to achieve fuel cycle lengths consistent with LWR operation with reasonable packing fractions and kernel diameters (the uranium enrichments considered in the figure range from 13.4 to 19.3%).

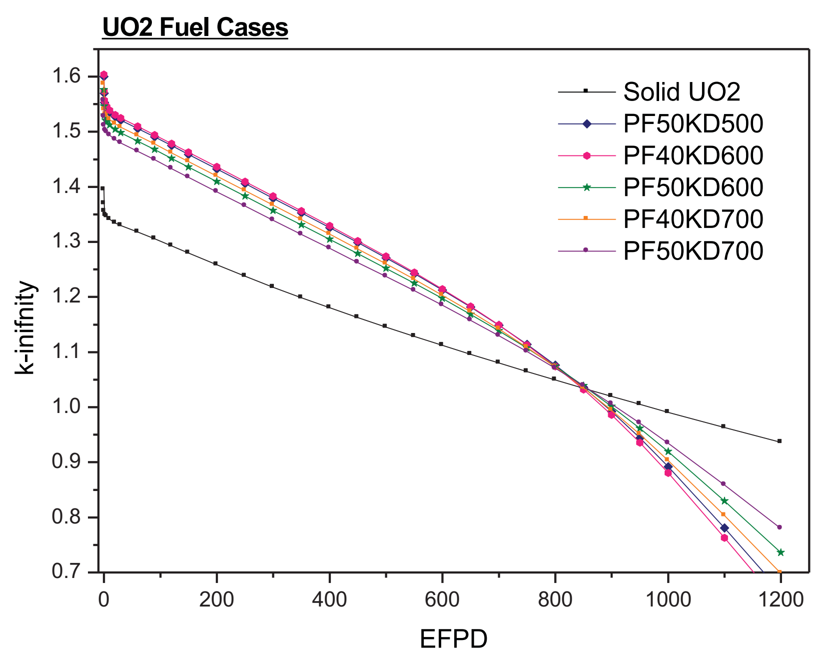

Figure 7. k_∞ behavior of UO_2 FCM fuel with increased diameter fuel pin (1.594 cm) in a relaxed lattice (pin pitch = 1.715 cm). PF = Packing Fraction; KD = Kernel Diameter.

4. CONCLUSION

This study shows that the use of standard UO_2 TRISO particles-based FCM fuel compacts in LWRs in a direct replacement of fuel pellets and the use of SiC for the cladding would result in unacceptably short cycles and in refueling outages perhaps as often as about every 100 days. This is clearly unacceptable from the point of view of the efficient operation of a LWR and the deployment of such fuel is highly improbable. However, this study also showed that through the use of a modified TRISO particle with a larger kernel, it is possible, from a neutronic standpoint, to extend the cycle length significantly, approaching ordinary LWR performance. Finally, it was shown that the use of a higher density fuel and larger kernels in tandem could result in cycle lengths that are even longer than those possible with current LWR fuel. Another set of considerations not carried out in the current study are those pertaining to the safety of the achievable designs. In particular, the safety parameters (i.e., reactivity coefficients) should be obtained for the entire cycle and for all cases. The principal neutronic-related conclusions are that (i) the naïve use of the FCM fuel with conventional UO_2 fuelled TRISO particles in LWRs is not practical but that (ii) other options appear to be neutronically viable. Such options should be pursued.

Results of preliminary calculations of fuel performance were also presented (i.e., quantification of predicted failure rates). Further studies should be carried out, however. In general, LWR conditions are significantly less taxing, from the point of view of temperature, than those prevailing in HTR designs, for which the TRISO particles have already been shown experimentally and in models to perform with no failures or with an insignificant rate of failures. However, the use of FCM fuel was shown here to require initial power densities within the kernels that are much higher than those in HTRs (before they eventually drop to lower values when the zone of fuel is in driven mode). These higher power densities may imply a different rate of radiation damage accumulation and retention. Furthermore, as the results presented here show, the larger kernel diameters used in conjunction with standard TRISO particle layer thicknesses may lead to excessive failures. TRISO particles with large kernels having buffer layers of increased thickness were predicted by the analyses to perform better. Further analysis would be required, however, to confirm this performance once fission product migration is better understood in the UN fuel. It follows that the material performance of the FCM TRISO particles (and that of the matrix material) should be evaluated both experimentally and through the use of models.

ACKNOWLEDGMENTS

Work supported by the U.S. Department of Energy (DOE), Office of Nuclear Energy (NE), under DOE Idaho Operations Office Contract DE-AC07-05ID14517.

REFERENCES

1. Petti, D. A., Buongiorno, J., Maki, J.T., Hobbins, R.R. and Miller, G.K.,. "Key Differences in the Fabrication, Irradiation and High Temperature Accident Testing of US and German TRISO-Coated Particle Fuel, and their Implications on Performance," *Nuclear Engineering and Design*, **222**, pp. 281-297 (2003)
2. Lyons, P., June,. Address at ANS Annual Meeting, Florida, (2011)
3. Pope, M. A., Boer, B., Ougouag, A. M., and Youinou, G., March. "Performance of Transuranic-Loaded Ceramic Micro-Encapsulated Fuel in LWRs; Interim Report, Including Void Reactivity Evaluation," INL/EXT-11-21343, Idaho National Laboratory. (2011)
4. Venneri, F., et al., "Fully Ceramic Microencapsulated Fuels: A Transformational Technology for Present and Next Generation Reactors - Preliminary Analysis of FCM Fuel Reactor Operation," *TransANS* vol **104**, pp. 671-674, June 26-30, 2011.
5. Snead, L. L., et al., "Fully Ceramic Microencapsulated Fuels: A Transformational Technology for Present and Next Generation Reactors – Properties and Fabrication of FCM Fuel," *Trans ANS* vol **104**, pp. 668-670, June 26-30, 2011.
6. Hussain, A., and Cao Xinrong, "Reactivity control technique for a pressurized water reactor with and inventive TRISO fuel particle composition," *Progress in Nuclear Energy*, **51**, pp. 742-745, (2009)
7. Hussain, A., and Cao Xinrong, "Small PWR core design with coated particle-based fuel with a novel composition," *Progress in Nuclear Energy*, **52**, pp. 531-535, (2010).

8. Hussain, A., and Cao Xinrong, "Reactivity feedback calculation of a conceptual TRISO fueled compact PWR core," *Progress in Nuclear Energy*, **53**, pp. 76-79, (2011).
9. Cai, X. et al. "Development of a thermal-hydraulic analysis code for the Pebble Bed Water-Cooled Reactor." *Nuclear Engineering and Design,* (2011), doi:10.1016/j.nucengdes.2011.09.007
10. Morris, R.N. and Pappano, P.J., "Estimation of Maximum Coated Particle Fuel Compact Packing Fraction," *Journal of Nuclear Materials,* **361**, (2007)
11. Nazaré, S., "Low Enriched Dispersion Fuels for Research and Test Reactors," *Journal of Nuclear Materials*, **124**, (1984).
12. Albarhoum, M., "Neutronic calculations of the U3Si LEU as a dispersed fuel for low-power research reactors," *Annals of Nuclear Energy*, **38**, pp. 2504-2508, (2011).
13. Marleau, G., Hébert, A., Roy, R., "A User Guide for DRAGON Version 4. IGE-294, École Polytechnique de Montréal", IGE-294, October (2008).
14. Hébert, A., "A Collision Probability Analysis of the Double Heterogeneity Problem," *Nuclear Science and Engineering,* **115** (2), pp. 177-184 (1993).
15. Hfaiedh, N., Santamarina, A., "Detemination of the Optimized SHEM Mesh for Neutron Transport Calculations," *Proc. Mathematics and Computation, Supercomputing, Reactor Physics and Nuclear and Biological Applications*, Avignon, France, 12 Sept. – 15 Sept. (2005).
16. Sengler, G.F., Foret, F., Schlosser, G., Lisdat, R. and Stelletta, S., "EPR Core Design," *Nuclear Engineering and Design*, 187, (1999).
17. DeHart, M.D., "TRITON: A Two-Dimensional Transport and Depletion Module for Characterization of Spent Nuclear Fuel," Oak Ridge National Laboratory, Tennessee. ORNL/TM-2005/39, (2009).
18. Todreas, N.E., and Kazimi, M.S., "Nuclear Systems I: Thermal Hydraulic Fundamentals," *Hemisphere Publishing Corporation*. pp. 296, (1990).
19. "Development Status of Metallic, Dispersion and Non-Oxide Advanced and Alternative Fuels for Power and Research Reactors," IAEA, Vienna, IAEA-TECDOC-1374, pp. 50 (2003).
20. Grover, S.B., Petti, D.A., Maki, J.T., "Completion of the first NGNP advanced gas reactor fuel irradiation experiment, AGR-1, in the Advanced Test Reactor," *Proceedings of HTR-2010*, Prague, Czech Republic, October (2010).
21. Boer, B., Ougouag, A.M., Kloosterman, J.L. and Miller, G.K., "Stress Analysis of Coated Particle Fuel in Graphite of High-Temperature Reactors," *Nuclear Technology*, 162, (2008).